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SOME TORNADOES, WATERSPOUTS, AND OTHER FUNNEL CLOUDS OF HAWAII

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ABSTRACT

During the 12 years 1949 through 1960, funnel clouds were observed over or near the Hawaiian Islands on 31 days. About half of these occurrences were waterspouts, but most of the other funnels remained aloft. Although none of the funnel clouds which reached or occurred over land during this period, or previously, appears to have attained the intensity or destructiveness of the major tornadoes of the continental United States, a number of them did minor damage.

The climatology and synoptic concomitants of funnel clouds in Hawaii are compared with those of similar events elsewhere, and the associated air mass properties illustrated by several proximity soundings.

Among the questions considered is whether the Hawaiian Islands serve merely as a vantage point from which to observe funnel clouds occurring over the nearby open seas, or whether through topography or otherwise they contribute to their formation. A close study of the pertinent circumstances suggests that while certain of the funnels may with some confidence be ascribed primarily to local or to synoptic effects, most of them appear to have involved the interaction of both.

1. INTRODUCTION

In the course of compiling a descriptive chronology of unusual weather events over the past 100 years in Hawaii [8], a number of instances of tornadoes, waterspouts, and other funnel clouds were encountered. While none of these compared in intensity with the major tornadoes of, for example, the North American continent, it was thought that a brief survey of their climatological and synoptic characteristics might be of some interest, particularly since tornadoes are accounted rare in the Tropics and—other than reports on occurrences in Bermuda [7, 13] and Fiji [10]—the literature contains little on the frequency, circumstances, and effects of funnel clouds in small oceanic islands.

2. CLIMATE OF HAWAII

GENERAL FEATURES

Hawaii is situated within the maritime Tropics and on the southern rim of the great semi-permanent anticyclone of the eastern North Pacific Ocean. Hence, its dominant weather regime is that associated with the prevailing east-northeasterly trades and with the trade inversion. In the mean these occur from about 60 percent of the time in the cooler half-year to over 90 percent during the warmer half-year and produce a characteristic distribution of orographic clouds and showers over the crests and slopes of the Islands.

Interruptions in the trades may last for from one or several days to a month or more. They occur chiefly from

October to April (the cooler half-year) and may be brought about by any of several events. Among these are the southward intrusion of a polar trough or cyclone, the downward building of an upper-level Low of tropical origin, and the passage of what, according to one's school of thought, may be regarded as a cold front or shear line or asymptote of convergence (probably all three occur). Closed surface Lows in the Hawaiian area, when accompanied by general rains and southerly winds, are referred to locally as "Kona Storms," [1] a term originally reserved for just such cyclonic circulations but now, particularly among the general public, coming more and more to signify any breakdown in the trades attended by widespread rain and winds from a non-trade direction.

In the absence of all these, and of a Pacific High near enough or strong enough to maintain the trades, pressure gradients in the Hawaiian area may become weak or diffuse inducing the stagnant conditions known locally as "Kona Weather" and characterized by light and variable winds, land and sea breezes, and afternoon convective clouds and showers over the interiors and uplands of the islands. When these intervals occur during the warmer half-year, particularly from later July through September, they include the warmest and most humid days of the year.

DESTRUCTIVE WINDS

Because their usual causes are lacking, destructive winds, like other severe weather, are rare in Hawaii. Tropical storms and typhoons, for example, are so infrequent that prior to 1950 they might reasonably have been assumed almost non-existent there. Since then, however, four have entered the area; but these have been so small, the region of strong winds so limited, and the influence of terrain so pronounced, that only on their closest approach was Hawaii much affected, and even then only the exposed portions of individual islands.

Thunderstorms also, although less uncommon than is generally supposed, are relatively mild—reflecting in part the absence of strong air mass contrasts in the central Pacific. They occur more frequently during the cooler half-year, usually with an upper trough or closed Low, and are accompanied at times by small hail, but seldom by high winds.

Occasionally, strong gusty trades from an exceptionally intense Pacific anticyclone have done minor damage to crops and flimsy structures, but a more usual setting for strong winds (although of brief duration) is the passage of a cold front or shear line, or of squalls embedded in the eastern semicircle of a Kona Storm.

Because of the extent, roughness, and diversity of the terrain, damaging winds in Hawaii are almost invariably localized and selective. Seldom does an entire island, despite its small area, everywhere experience high winds at the same time or from the same cause. In some instances these have been readily traceable to local funnelling or buffetting, or to some other topographic effect (and, conversely, their absence to sheltering in a lee); while at other times they seem to be associated with migratory perturbations too small to be caught in the sparse synoptic net. It seems certain, in any event, that the Islands impress a considerable orographic component on the wind, as they do on rainfall. Unfortunately, the absence of a site near enough to experience the same synoptic events, and small and flat enough to do so without topographic (or other local) distortion, precludes distinguishing between the two.

3. THE DATA

The period covered by this report, August 1948 through December 1960, comprises approximately the final 12 years of the compilation, "One Hundred Years of Hawaiian Weather" [8], and is that for which both the synoptic data and the local observations are most complete and reliable. For these 12 years manuscript synoptic charts for the surface and several upper levels, and radiosonde and other data essential to an interpretation of the meteorological circumstances under which the events occurred, were also readily available in Honolulu. Principal sources of information on the occurrence of funnel clouds included the published *Climatological Data*, Hawaii Section, monthly and annual summaries; the surface weather observations (WB Form 1130); a weather log maintained at WBAS, Honolulu, for part of the period; the daily and weekly newspapers published in Honolulu and elsewhere in Hawaii; and all other periodicals and publications in which such data might be contained.

4. NUMBER AND TYPES OF FUNNEL CLOUDS IN HAWAII

For the earlier portion of "One Hundred Years of Hawaiian Weather" [8], it was necessary to rely almost exclusively upon newspaper reports. These become increasingly fragmentary as one goes back in time. Times of occurrence, and details from which the precise nature of the phenomenon and the attendant meteorological circumstances might be inferred, are often lacking; and fewer of the significant weather events appear to have found their way into the record at all, to await later rediscovery. Thus, for example, a thorough sifting of all available material from 1860 to 1890 unearthed an average of only five funnel clouds per decade, while a similar search from 1951 through 1960 found 28.[2] (The recent apparent rise in tornado frequency in the continental United States is similarly due, almost certainly, to improvements in the reporting and retention of observations.)

The unreliability of ordinary recollection in estimating the frequency even of the unusual is suggested by the following comments which appeared at various times in

[1] The word "Kona" is from the Polynesian, and means *leeward* (relative to the trades), or *southerly*.

[2] Only explicit funnel cloud sightings are included. High or damaging winds which on the basis of circumstantial evidence *might have been* rotatory have not been included.

the Hawaiian press following the sighting of a funnel cloud in the Honolulu area.

In April 1864: "These are seldom seen here."

In May 1866: "These have been quite frequent about the islands."

In January 1906: "Waterspouts are rarely seen. This is the second in recent years."

In January 1927: "Believed first ever seen . . ."

In March 1933: "According to the Weather Bureau, an average of about one waterspout per year is reported off the port of Honolulu."

These remarks may be compared with the frequencies given just previously.

Between October 1948 and December 1960, funnel clouds were observed on 31 days.[3] On four occasions they occurred on successive days, so that it might be more accurate to speak of 27 funnel cloud situations during this period. Often two or more funnels were observed at the same time, or in sequence, or in different places on the same day; and these were counted as a single occurrence. Thus, "occurrence" and "day" will be synonymous thenceforth in this paper, unless explicitly stated otherwise—as, for example, when specific funnels are related to specific soundings.

Of the 31 observations, 16 were of waterspouts. Four others were described in the original reports as, respectively, "probably a small tornado," "large dust devil," "tornado," and "baby tornado." In 11 instances the funnel did not reach the earth's surface. At least 22 of the 31 funnels occurred offshore and no more than 9 over land.

A tabulation by year and type is given in table 1. Of the twelve full years shown, five had no funnel cloud reports at all, and four years had five or more.

The geographic distribution of the reports is shown in figure 1. Unfortunately, the scale of the map does not permit the diverse and complex topography of the islands to be depicted. The clustering along the south shore of Oahu and through its central saddle is almost certainly more of demographic, than of meteorological, significance. In fact, the plotted symbols pretty well reflect the location of weather stations and the population density—a relationship noted, also, in the continental United States. This is not to say that meteorological factors play no role in determining where and when funnel clouds in Hawaii occur, but rather that these may be outweighed by the extremely non-uniform distribution of potential observers.[4]

Further, since the failure of funnels to pose the treat in Hawaii that they do in other places may keep casual observations of them from finding their way into the record, it is at least as true in Hawaii as elsewhere that fewer funnel clouds are observed than occur, and reported

TABLE 1.—*Number of days, and types of funnel clouds in Hawaii by years, 1949–1960*

Year	Waterspouts	Funnels aloft	Other	Total
1949	0	0	0	0
1950	2	1	0	3
1951	4	1	0	5
1952	3	1	0	4
1953	0	0	0	0
1954	0	0	0	0
1955	4	0	1	5
1956	1	2	2	5
1957	0	2	1	3
1958	0	0	0	0
1959	0	0	0	0
1960	2	4	0	6
Total	16	11	4	31

than observed. In view of all this, 31 funnel cloud days in 12 years over or near an area of only 6,500 sq. mi. may well represent a rather high frequency, even by North American standards.

In this connection, it is, of course, pertinent to ask again whether the Islands merely provide a vantage point from which to observe funnel clouds over the open sea, or whether they contribute through topography or otherwise to their formation. While this is not a question to which an unequivocal answer may ever be possible, a consideration of the synoptic circumstances under which funnel clouds have occurred in Hawaii during the past 12 years, and of their diurnal and seasonal variations, may permit tentative conclusions to be drawn concerning the relative importance of large-scale and local influences.

5. CONDITIONS FOR FUNNEL CLOUDS IN HAWAII

In regions of high data density, such as the continental United States, detailed analyses of atmospheric pressure, temperature, humidity, wind, stability, etc., have apparently succeeded in defining a number of the conditions conducive to the occurrence of tornadoes (more specifically, of those which occur in thunderstorm-producing situations) and are routinely employed in delineating tornado-prone areas for warnings and forecasts. This approach is, of course, precluded in the central Pacific, where an area larger than the United States, centered on Hawaii, encompasses at most four upper air stations, including the two in the Islands; and where even the surface observations, although augmented by ship reports, ordinarily resolve only the grosser features of the circulation.[5]

Consequently, the following discussion of the tabulations in tables 2–4 is intended only to suggest in a most general way the synoptic circumstances under which funnel clouds have occurred in Hawaii during the 12 years under consideration, and the weather which accompanied them; and is not to be taken as defining necessary or sufficient

[3] Wolford [14], who necessarily drew upon a less complete survey, lists for Hawaii 2 tornadoes in the period 1916–1958, 1 waterspout (1948–1958), and no funnels aloft (1953–1958).

[4] Oahu has nearly 80 percent and Honolulu half the total population of the State. Large portions of the other islands are but sparsely inhabited, and the bulk of their populations concentrated in a few small towns.

[5] Nor is it, for similar reasons, applied off the Gulf States and in other coastal regions of the continental United States. It may be of interest to note, also, that the standard tornado forecast zone used there has several times the area of the Hawaiian Islands.

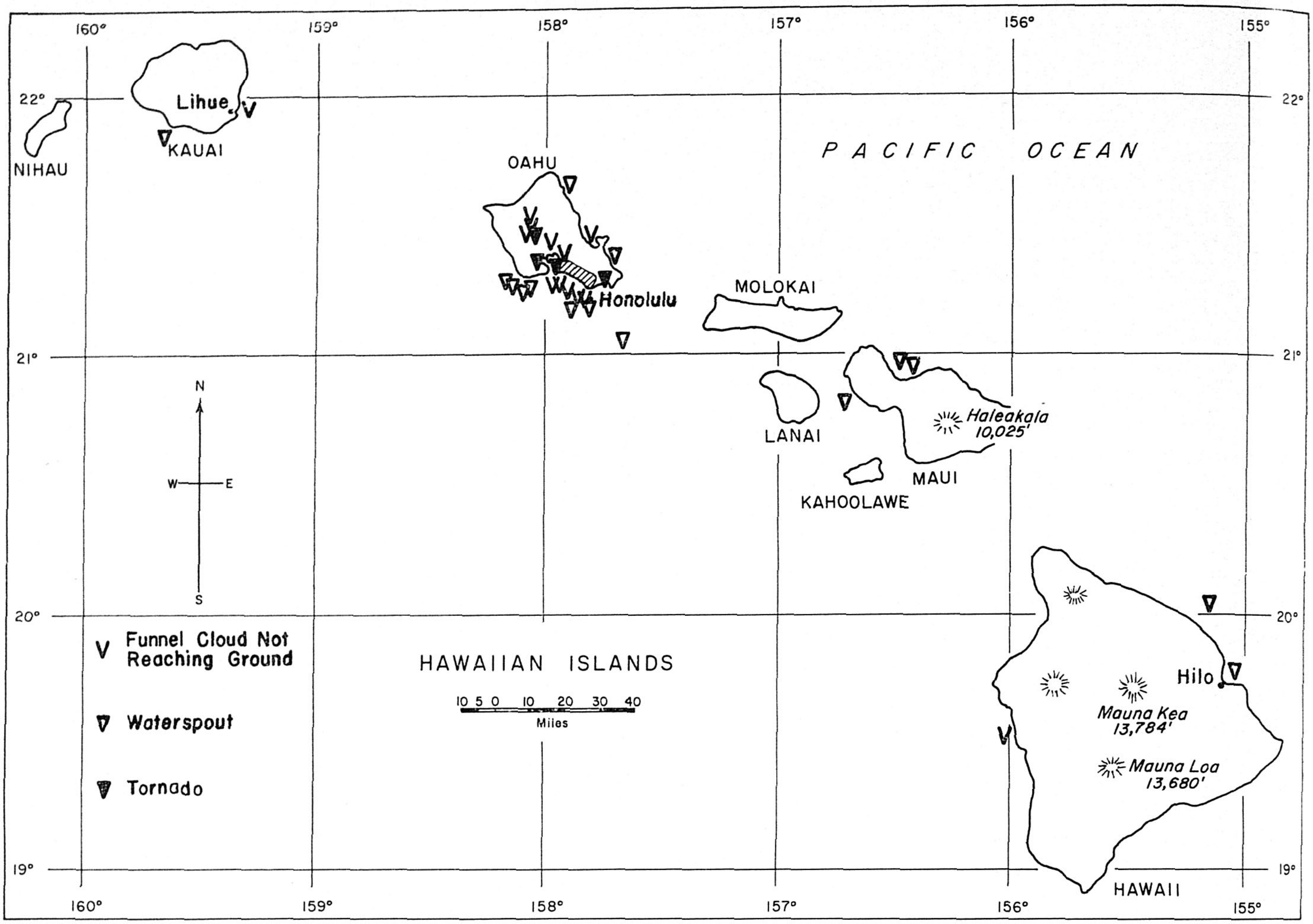

FIGURE 1.—Funnel clouds in the Hawaiian Islands from October 1948 to December 1960. The large number over and near Oahu may reflect the concentration of population in that area.

conditions for their occurrence or criteria useful in prediction.

Funnel clouds appear to have occurred during each of Hawaii's principal synoptic regimes, although not at all in proportion to the climatological frequencies of those regimes. Thus, while the Pacific High both climatologically and physically dominates the circulation in the northeastern Pacific, it figured prominently on only 4 of the 31 funnel cloud days; and these funnels all occurred in the lees during strong and gusty trades, and may therefore have been topographically induced.

In contrast, the more "typical" funnel cloud days (there were 21 such) had weak or ill-defined surface pressure gradients. Winds were correspondingly light and variable, with sea breezes and convective cloud becoming widespread as the day progressed. Afternoons were frequently warm and humid enough to qualify as the Kona Weather described earlier (and to be reminiscent, as well, of the "cyclone weather" [3] often preliminary to tornado outbreaks in the central United States). Interestingly enough, on 5 of the approximately 7 days when funnels occurred inland the high temperatures and humidities drew special comment. One was described in the press as a "steam bath"; another was the warmest day of that year (88° F. on August 3, 1952).

Of these 21 typical funnel cloud days, 10 had very light trades in the mornings along well-exposed windward shores, thus confirming (despite the flat pressure gradients) the pervasive influence of a distant or weak Pacific High, or of a slight ridge; but these trades invariably gave way to sea breezes later in the day.

Funnels were associated also with Kona Storms, although only on two days, with surface troughs (on three days) and, in one instance, with a well-marked cold front or shear line.

The concurrent upper level synoptic charts (principally those at 500 mb.) fell rather readily into only three broad categories. Flat pressure gradients, although not as common aloft on funnel cloud days as they had been at the surface, were present on 11 of those 31 days. Also

Table 2.—*Conditions associated with funnel clouds in Hawaii, 1949–1960*

	Number of days observed
1. *Surface winds*	
Light and variable, with sea breezes in p.m.	14
Weak trades in a.m. along exposed windward shores, with sea breezes in p.m.	10
Strong trades	4
Other	3
Total	31
2. *Weather (most severe observed)*	
Thunderstorms or lightning in Hawaiian area	12
Convective showers:	
Heavy	6
Moderate	3
Light or scattered	5
Towering cumuli	2
Fine weather	3
Total	31
3. *Surface synoptic chart in Hawaiian area*	
Flat pressure gradient:	
Weak or diffuse High or ridge	10
Col (includes 6 days in category just above)	14
Other	3
Subtotal, flat gradient only	21
Strong High	4
Trough	3
Kona Storm (closed Low)	2
Cold front or shear line	1
Total	31
4. *Upper-level synoptic chart in Hawaiian area*	
Flat pressure gradient	11
Trough or closed Low directly aloft	11
Trough line or closed Low to west	9
Total	31

on 11 days a trough or closed Low was evident directly over the Islands, and on 9 other days the trough line or closed low center, while still somewhat to the west, lay by extrapolation within a day's distance (from about 200 to 500 mi.).

Classification was not always easily arrived at or unambiguous. For example, it was difficult to decide whether certain surface and upper air patterns would be more properly described as a diffuse High, or as a col, or perhaps, even as a weak trough. Each such decision was finally based on a reexamination of the data, on continuity, and on the views of skilled analysts—the latter being elicited without reference to the purpose of the classification.

On some funnel cloud days, particularly the many with ill-defined surface pressure gradients, the sparseness of the data on which the analysis was based did not permit ruling out the possible presence of other synoptic entities, and hence their contribution to the release of instability. On eight such occasions cold fronts or shear lines, previously dropped from the charts or crossing the Pacific to the north, *could* by continuity or extension have been traversing the Hawaiian area; and on several of the 11 days (not mutually exclusive with those in other categories) when the Islands lay within a col or a long narrow trough extending from a Low far to the north southward between Highs to the northeast and northwest of Hawaii, a streamline analysis, supported perhaps as much by a progressing band of clouds and showers as by the meager wind data, might have suggested an asymptote of convergence in the vicinity of Hawaii.

Most days with funnels had other convective phenomena, as well: on 12, thunderstorms or lightning occurred in the Hawaiian area; on 14 others, convective showers, which ranged from heavy to light and scattered; and on 2, towering cumulus clouds. Except for clouds, however, these apparently seldom occurred in immediate conjunction with the funnels, themselves. Thus, only twice did observers explicitly associate funnel clouds with rainfall (in both instances heavy showers fell from clouds into which a funnel had just withdrawn); but this may imply nothing more than the incompleteness of the reports.

Yet, although only three of the funnel cloud days were entirely without convective clouds and showers, most of Hawaii's funnels would seem to have occurred predominantly during fair, as distinct from foul, weather. In

Table 3.—*Concurrent surface and upper level synoptic situations in the Hawaiian area on funnel cloud days, and the associated weather, 1949–1960*

Aloft	Surface: Flat pressure gradient: Col	Weak High	Other	Strong High	Trough	Kona storm	Cold front or shear line
Flat Pressure Gradient	⌂ ▽-	▽ (2) ▽-	▽= ▽	⌂ ○ (2)			⛈
Trough or Closed Low	⛈ ϟ ▽= (2)	ϟ ▽= (2)	⛈		⛈ (3)		
Trough or Closed Low to West	⛈ ▽	⛈ ▽= ▽- ▽		○		⛈ (2)	

⛈ Thunderstorm
ϟ Lightning
▽= Heavy convective shower(s)
▽- Moderate convective shower(s)
▽ Light or scattered convective shower(s)
⌂ Towering cumuli
○ Fine, dry weather
( ) Number of observations, if more than one

TABLE 4.—*Percent of possible sunshine on funnel cloud days in Hawaii, 1949–1960*

Possible sunshine greater than (percent)—	Number of days	Percent of days
90	3	11
80	8	26
70	15	48
60	19	61
50	23	74
40	27	87
30	28	90
20	28	90
10	30	97
0	31	100

fact, as table 4 shows, only 4 of the 31 funnel cloud days had less than 40 percent of the sunshine possible on those days, while nearly half had more than 70 percent.

That more than simple convection over a heated island, or even the resultant convergence of the sea breezes which, in the absence of a synoptic wind, spring up everywhere along the island shores, may have been involved on funnel cloud days in Hawaii is suggested by the tendency for the weather to be intensified by an upper trough or Low. Thus, as table 3 shows, of the 12 instances of thunder or lightning and the 6 of heavy convective showers, only 2 occurred on the 11 occasions when pressure gradients aloft were flat and the remaining 16 on the 20 days when an upper trough or Low was present.

Most conspicuously absent were the squall-line funnel clouds of the continental United States. Only one of Hawaii's funnels—a waterspout—occurred during an unmistakable cold front or shear line passage. Similarly, the association with thunderstorms—so close and significant that, according to [12], "tornado forecasts are not currently issued for areas in which thunderstorms are not expected" does not hold in Hawaii, where thunder or lightning was observed on only 12 of 31 funnel cloud days, and in no known instance in the immediate vicinity of a funnel.

6. DIURNAL VARIATION

Times of occurrence are closely known for 22 of the 31 Hawaiian funnel clouds and approximately (e.g., "early afternoon") for three others. For the remaining six, no time could be established. On days with more than one funnel cloud, the time of the earliest was used. The resulting diurnal distribution is shown in figure 2.

The pronounced afternoon maximum, with 72 percent of all observations falling between 1500 and 1900 HST, rather closely resembles that for tornadoes in the Nebraska-Iowa-Dakota-Minnesota area (see fig. 8 of [12]), but is even more sharply peaked.

The implied importance in both regions of such a diurnal mechanism as surface heating in steepening lapse rates and releasing latent instability is supported in Hawaii by the tendency already discussed for funnel

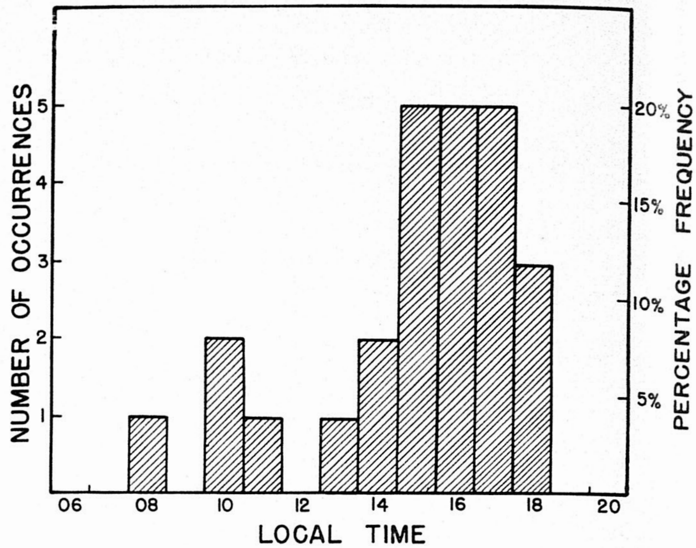

FIGURE 2.—Diurnal variation of the number and percentage frequency of funnel clouds in Hawaii during the hours beginning at the indicated hours.

clouds to occur with other convective phenomena and in situations which favor afternoon heating and sea breeze convergence.

The relatively small number of funnel clouds observed during the morning and early afternoon presumably means only the obvious—that conditions are then less favorable to their development; but the rather abrupt decrease after about 1800 HST would seem to be due, at least in part, also to the difficulty of seeing them after dark—a difficulty which, while it undoubtedly reduces also the frequency of nocturnal tornadoes observed in the continental United States, is especially effective where, as in Hawaii, most funnels remain aloft or out to sea.

There is some indication, also, that funnels tended to form somewhat earlier on those days, mentioned previously, when gentle morning trades along windward shores [6] were later replaced by sea breezes. Thus, 6 of the 10 funnels which occurred prior to 1600 HST (excluding the 2 which accompanied Kona Storms), but only 2 of the 13 which occurred later than 1600 HST were on days of this type.

The grouping of data may, of course, be entirely fortuitous. Certainly the mechanism responsible for such an advancement of the time of onset would be by no means clear. It is, however, obvious that the reinforcement of the light trades by sea breezes along the windward coasts and their interactions elsewhere would greatly distort the relatively simple flow patterns associated with peripheral onshore motion. The additional complexity introduced by the dynamic and thermal effects of topography places the resultant convergence patterns beyond analysis, for the purposes of the present report.

[6] "Windward" in Hawaii refers always to the trades, not to the observed wind.

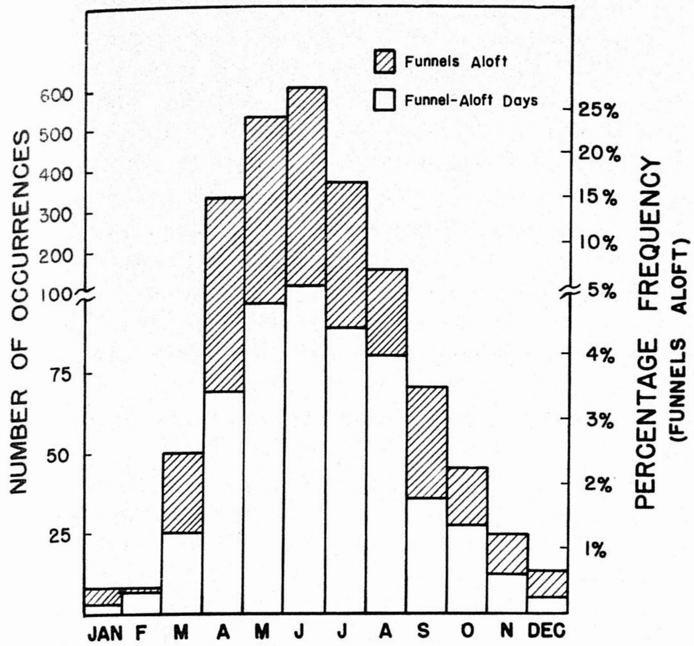

FIGURE 3.—Annual variation of the number and percentage frequency of funnels aloft and funnel-aloft days in the United States (from table 11 of [14]).

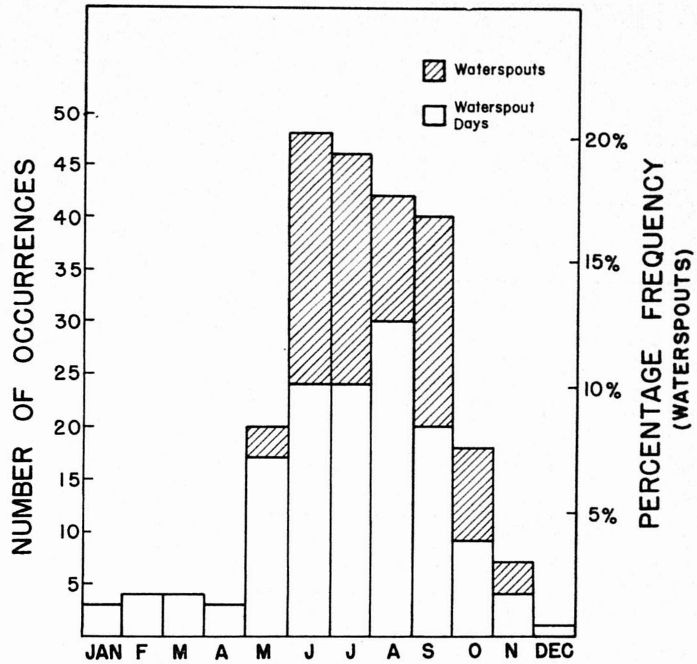

FIGURE 4.—Annual variation of the number and percentage frequency of waterspouts and waterspout days in the United States, excluding Hawaii (from table 10 of [14]).

7. SEASONAL VARIATION

Although, as has already been pointed out, the diurnal variation of funnel clouds in Hawaii strongly resembles that of tornadoes in the continental United States, their seasonality does not.

Tornado frequency in the central United States has a single seasonal peak. This appears in late winter or early spring in the Gulf States, in spring in the Southern Plains, and in summer in the Central and Northern Plains; a migration which may reflect the northward shift of the regions of greatest air mass contrast.

But since most Hawaiian funnel clouds are waterspouts, or remain aloft, their annual variation might more appropriately be compared to that of similar phenomena elsewhere. As shown in figure 3, the monthly distribution for the United States as a whole of funnels aloft and funnel-aloft days (the latter are perhaps more indicative of the frequency of favorable conditions) is much like that for tornadoes: a winter minimum, and early summer maximum, a rapid but steady increase in spring and decline in autumn.

Waterspout seasonality (fig. 4) displays important differences. The winter minimum is much longer, extending from December through April, and the late spring rise to the June peak is more abrupt. However, unlike the sharp maxima of tornado and funnel cloud frequencies, the number of waterspouts decreases but little from June through September. Waterspout days do not reach their highest frequency until August, and there are many more waterspouts and waterspout days in September than in May.

The long, retarded winter minimum, the prolonged maximum, and the slow decline in frequency until later summer suggest the maritime influence in regions where waterspouts occur, and specifically the seasonal lag in sea surface temperatures; perhaps an expected association in view of the relationship of convection to the temperature of the underlying water surface.

Despite their important differences, however, the frequency distributions of tornadoes, funnels aloft, and waterspouts in the continental United States are alike in having a single and well-defined annual peak in late spring or in summer.

Seasonality in Hawaiian funnel clouds is less explicit. Figure 5 would appear to imply a bimodality corresponding to Hawaii's warmer and cooler half-years (April to October, and October to April), the seasons having 14 and 17 funnels, respectively, and the transition months of April and October none. The neatness of this partitioning, however, should not obscure its being based on only 31 observations; and Hawaii's funnel clouds may in actuality be more evenly distributed through the year.

There would seem to be also some tendency for funnels to remain aloft in the warmer half-year (9 out of the 14 which occurred in that season did so) and to become waterspouts in the cooler half-year (13 out of 17). The latter seasonality, especially, is strikingly unlike the summer maximum of waterspouts elsewhere in the United States, although there and in Hawaii sea surface

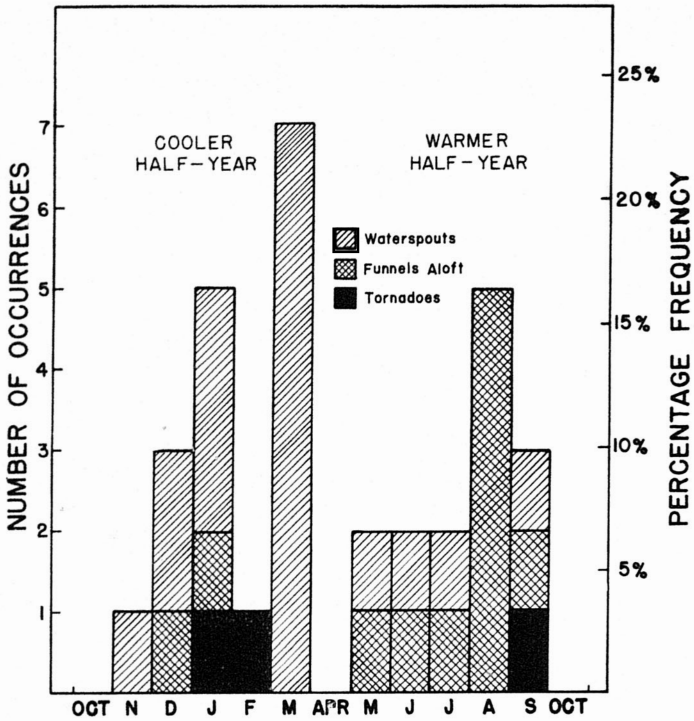

FIGURE 5.—Annual variation of the number and percentage frequency of funnels aloft, waterspouts, and tornadoes in the Hawaiian Islands. The apparent bimodality may be a fortuitous outcome of the small number of observations.

temperatures and air-sea temperature differences have very similar annual variations.[7]

But whatever the validity and significance of the implied annual variation of Hawaii's funnel clouds, there does appear to be a rather marked seasonal difference in frequency of some of the circumstances under which they occur. Certain of these events are almost exclusively of the cooler half-year; for example, Kona Storms and cold fronts. Others are more frequent then, but occur also in the warmer half-year: thunderstorms, upper troughs and Lows, and the cold fronts and shearlines trailing toward Hawaii from Lows or polar troughs crossing the Pacific to the north. On the other hand, it would appear that the flat pressure gradients at the surface and aloft, so common on funnel cloud days, and the possibly weakly convergent regions south of cols, are about as likely in one season as in the other.

8. VERTICAL DISTRIBUTION OF TEMPERATURE AND HUMIDITY NEAR FUNNEL CLOUDS

The importance of issuing tornado warnings in the continental United States has directed much attention there to the properties of the air masses within which these phenomena occur. While it had perhaps been hoped that soundings made near and just prior to tornado occurrences would disclose certain unifying similarities, possibly of diagnostic or even predictive value, in fact a wide variability became evident. Part of this could be attributed to the separation in time and space between these "precedent soundings" and the tornadoes themselves, part to the rapidity with which local air mass properties appeared to change during this precursory period, and part, also, to the possible invalidity of the notion that specific necessary and sufficient antecedents do exist.

One generalization which did emerge was that tornado-prone air masses frequently possess a lower moist layer and an upper dry layer, separated by an inversion, and are usually conditionally and convectively unstable to some depth. "Proximity soundings" made even nearer tornadoes (within 50 mi. and 1 hr. prior) confirmed that air mass properties that near tornadoes could differ significantly from those within the same air mass at greater distances in time and space, and demonstrated specifically the frequent deepening of the moist layer and the weakening or disappearance of the capping inversion [1].

TYPICAL AND FUNNEL CLOUD SOUNDINGS IN HAWAII

Radiosonde observations in the Hawaiian Islands are presently made twice daily at Lihue, Kauai, and at Hilo, Hawaii; and, until May 1953, were also taken at Honolulu. Prior to May 1957 these were at 0500 and 1700 LST, and since then at 0200 and 1400 LST.

The "typical" sounding is that associated with the trades, or more particularly with the southwestern periphery of the Pacific High. A type frequently seen is shown in figure 6. Although these soundings vary greatly, their distinctive feature is, of course, the subsidence (trade) inversion which, in the Hawaiian area, usually occurs at 5,000 to 8,000 ft. above sea level. The air below the inversion, having been rather thoroughly mixed during its long oceanic trajectory, has a lapse rate near the dry adiabatic and a relative humidity which increases somewhat with height and reaches its maximum at the inversion base or in clouds below, depending on the path of the balloon. Moisture decreases rapidly through the inversion and above, often becoming too low for accurate measurement by the radiosonde's humidity element ("motorboating" occurs). The sounding is convectively unstable throughout and—except through the inversion—conditionally unstable, as well. Layer lifting of the trades over the various island barriers, however, is ordinarily insufficient to release this instability unless an easterly wave or upper trough has previously raised, weakened, or destroyed the capping inversion. The heavier trade wind showers occur in this very circumstance.

Since in most of the synoptic regimes which interrupt or replace the trades the subsidence inversion is weak or

[7] Average sea surface temperatures near Hawaii vary from a maximum of 79° F. in September to a minimum of 74° F. in February [6]. The mean annual range of about 5° F. is substantially less than that for other regions in the United States subject to waterspouts, as is the average maximum air-sea temperature difference of about 3° F. [11], which in Hawaii occurs from November through February.

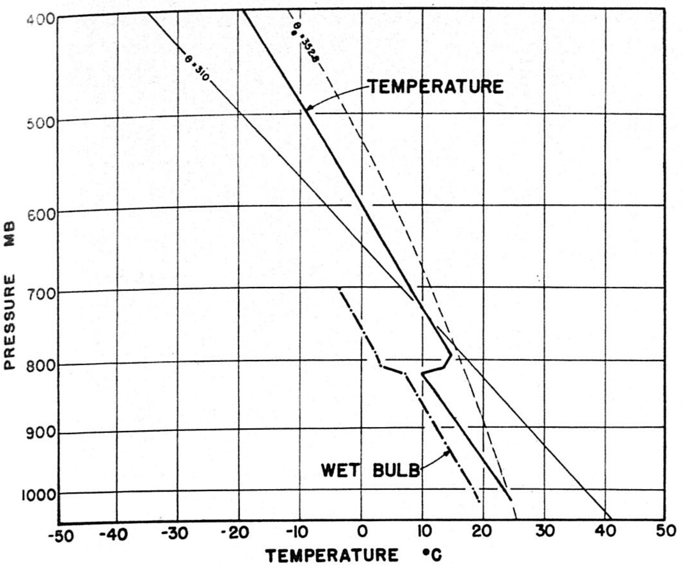

FIGURE 6.—"Typical" trade wind sounding, Honolulu, Hawaii, 0300 GMT April 11, 1952 (1700 HST April 10). The light solid line is the 300° K. dry adiabat and the light broken line the 352.8° K. moist adiabat.

lacking, vertical motions more intense, the moist layer deeper, and the temperature lapse more nearly moist adiabatic, the transition period, although ordinarily not involving a frontal passage, may be marked by air mass changes like those which in the continental United States sometimes usher in thunderstorms or tornadoes. In Hawaii, however, soundings of this type are quite commonplace and occur even during generally fair weather; and, in general, there is great diversity among soundings within and between the various synoptic regimes.

On the 25 days when funnels occurred at known times, 11 funnels were within 30 mi. and 3 hr. of a scheduled radiosonde observation, and 10 of these within 20 mi. and 2 hr. Six of the 11 preceded and 5 followed the balloon release time. (The termination in May 1953 of radiosonde observations at Honolulu, near where most of the funnels were observed, left Lihue, approximately 90 mi. away, as the nearest release point and hence greatly reduced the likelihood of obtaining proximate radiosonde and funnel cloud observations.)

Since funnel clouds in Hawaii do not ordinarily occur along fronts or in other situations which accompany the transition from one air mass to another, it seemed reasonable to consider first what characteristics these six pre- and five post-soundings might have in common, and then to compare them with one another and with the others more remote in time and space.

No resemblances or differences evidently related to their distance in time or place from funnel cloud occurrences could be discerned, but only those ordinarily found within and between the various Hawaiian synoptic

TABLE 5.—*Frequency of certain properties of soundings on funnel cloud days in Hawaii, 1949–1960*

1. *Inversion or isothermal layer below the 700-mb. level:*

Inversion	Isothermal	Neither	Total
11	3	17	31

2. *Depth of moist layer (in mb.):*

Below:	900	800	700	600	500	Over 500	Total
		8	22	26	29	2	31

3. *Dry adiabatic layer(s) below the 700-mb. (excluding surface layer in afternoon soundings):*

Present	Absent	Total
19	12	31

regimes. The subsidence inversion typical of air within the trade wind belt (although often absent even there) was lacking on most, but present on some, although seldom intense. The moist layer was in most instances shallow. Many of the soundings were convectively and conditionally unstable in part or in whole, and contained layers having a dry adiabatic lapse. Several of these frequencies are summarized in table 5.

On a number of occasions, particularly in the absence of an inversion, latent or convective instability could have been released by a reasonable degree of parcel or layer lifting, although the latter was rendered less likely by the weak pressure gradients and very light winds which prevailed on many funnel cloud days.

PROXIMITY SOUNDINGS FOR HAWAIIAN FUNNEL CLOUDS

The five soundings nearest to and most immediately preceding funnel cloud occurrences in Hawaii are shown in figures 7 to 11, together with those made 12 hr. earlier and later. For convenience, these will be referred to hereafter as the *antecedent*, *proximate*, and *subsequent* soundings, respectively. To facilitate comparisons with tornado proximity soundings in the continental United States, which are often discussed in terms of such measures of stability [8] as the levels of condensation and free convection, and of the Showalter Index,[9] these are given in table 6 for the Hawaiian soundings. Some of the pertinent features of these soundings will be touched on below, together with the synoptic conditions and weather associated with them.

(1) *March 3, 1950, 1700* HST, *three miles south of Barber's Point, Oahu.*—This funnel was first observed within a very few minutes of the 1700 HST (0300 GMT) radiosonde release from WBAS, Honolulu, about 11 mi. to the east. It extended 800 ft. below the cloud base and lasted about

[8] The significance of these is sometimes overrated. Their sensitivity to conditions in the lowest layers, and to the potential temperatures and mixing ratios selected to represent these, greatly reduces the objectiveness of the computations, although they may still be of some interest in large changes and when the intercomparisons are made by the same person.

[9] The Showalter Index [9] is obtained by subtracting from the observed 500-mb. temperature that of a parcel which ascends dry and then moist adiabatically to that level from 850 mb. Hence, negative values (parcel temperature greater than environmental temperature) indicate parcel instability and positive values parcel stability.

TABLE 6.—*Stability indexes and other characteristics of proximity soundings for funnel clouds in Hawaii, 1949–1960*

Date and time (GMT)	Sounding	Top of moist layer (or of moisture break)	"Motor-boating" begins (mb.)	Lifting condensation level (mb.) (1)	Lifting condensation level (mb.) (2)	Level of free convection (mb.) (1)	Level of free convection (mb.) (2)	Showalter index (° C.)	Lifted index (° C.) (1)	Lifted index (° C.) (2)
0300 April 11, 1952	"Typical Trade"	820 mb.	700	860	910	*830	*850	6.7	3.8	2.8
1500 March 3, 1950	Antecedent	#820	500	910	1000	*850	*895	9.4	8.2	5.4
0300 March 4, 1950	*Proximate*	810	700	905	940	*825	*910	7.6	6.4	3.6
1500 March 4, 1950	Subsequent	800	700	920	990	*870	NR	11.5	8.5	10.0
1500 May 31, 1951	Antecedent	#815	above 400	915	940	*820	*910	1.5	0.7	−1.8
0300 June 1, 1951	*Proximate*	#820	400	905	905	NR	*SFC	7.6	3.9	0.0
1500 June 1, 1951	Subsequent	#820	400	905	990	NR	NR	5.3	3.9	3.8
0300 March 2, 1952	Antecedent	350	none	920	SFC	920	SFC	1.9	−5.7	−11.0
1500 March 2, 1952	*Proximate*	850	700	890	980	*860	910	6.0	2.5	−0.5
0300 March 3, 1952	Subsequent	810	700	900	965	*860	960	4.2	0.0	−5.5
1500 March 3, 1952	Antecedent	#700	#600	880	960	NR	NR	2.4	0.8	3.5
0300 March 4, 1952	*Proximate*	860	700	890	930	890	930	−1.0	−5.9	−8.5
1500 March 4, 1952	Subsequent	950	750	895	960	*850	*600	10.7	−1.3	0.0
1500 March 18, 1955	Antecedent	800	600	900	970	*725	NR	1.0	−1.2	3.6
0300 March 19, 1955	*Proximate*	650	625	905	950	*770	950	1.5	0.5	−7.5
1500 March 19, 1955	Subsequent	700	600	915	975	755	NR	0.0	−0.4	5.7

(1) Based on mean values of potential temperature and mixing ratio in lowest 100 mb.
(2) Based on surface values of potential temperature and mixing ratio.
#Moisture increases again at higher levels.

*Layer of positive buoyancy capped by inversion or other stable layer.
NR—Not Reached: parcel did not reach level of free convection.
SFC—Surface: level of free convection was at surface.

8 min. Whether the funnel reached the sea could not be determined from the observer's position, but it was soon followed by another which did.

At the time, Hawaii was far southwest of a moderate Pacific High. Pressure gradients at the surface and aloft were very weak, and the winds light and variable to over 10,000 ft. This was one of several successive days of fine weather. On the previous day, very light trades had been supplanted in mid-morning by sea breezes. By early afternoon on March 3, sea breezes were again developing along the coasts, and some convective cloudiness inland. Only a few light and scattered showers were observed.

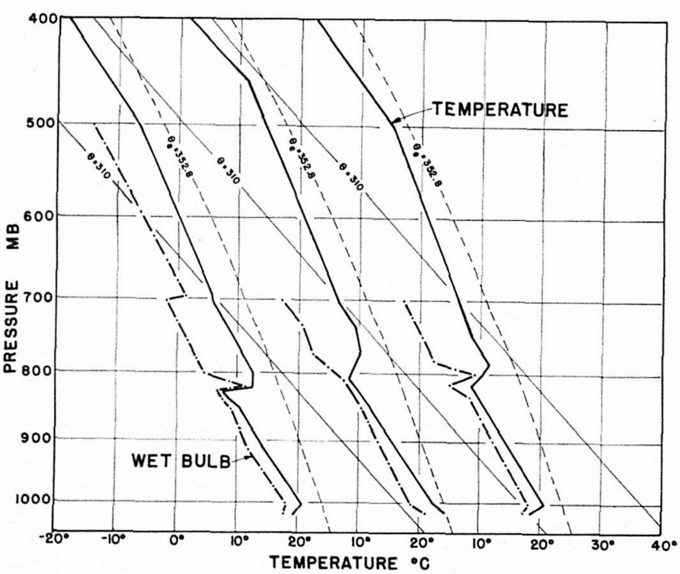

FIGURE 7.—Funnel cloud proximate sounding (center), Honolulu, Hawaii, 0300 GMT March 4, 1950 (1700 HST March 3), made within a few minutes and 11 mi. east of a long suspended funnel which may have been a waterspout. Soundings to left and right are the *antecedent* and *subsequent* soundings, respectively, taken approximately 12 hr. before and after the *proximate* sounding.

All three of the soundings for this period (fig. 7) possess the temperature inversion characteristic of the subsiding air within the southwestern rim of the Pacific anticyclone (see fig. 6 for comparison), and all are conditionally and convectively unstable from the surface to the inversion base. On the proximate sounding, the inversion is slightly higher and less intense than in either of the others, moisture drops sharply with motorboating above the 700-mb. level, and convective instability is present throughout.

The Showalter Index shows the soundings to be stable for parcel ascents from 850 mb.; but the proximate sounding is least so. The lifting condensation levels remain below the 900-mb. level which agrees well with observed cloud base heights, but the positive buoyancy layers above the levels of free convection are shallow and capped by the inversion.

On the whole, then, the air mass, while thermally stratified and stable, would appear to have been slightly less so shortly before the funnel occurred than it was 12 hr. before or after; but even with afternoon heating (note the replacement of the nocturnal ground inversions by a superadiabatic surface layer in the proximate sounding) the inversion would have prevented the development of deep convection, as—in fact—the observed weather suggests it did.

(2) *May 31, 1951, 1800* HST, *off southern Kauai.*—This waterspout, apparently the only one in the area, was sighted from an aircraft 16 mi. west-southwest of Lihue, Kauai, and about 1 hour after the 1700 HST (0300 GMT) radiosonde release from that station.

This was a day of fresh trades from a High 1,000 mi. northeast of Hawaii, and gusts frequently exceeded 25 m.p.h. during the afternoon. The waterspout, which occurred a short distance offshore in the island lee, may have been topographically induced; but there is no way to verify this. Otherwise, except for scattered trade wind clouds and showers, the weather was fine and dry. Aloft there was some suggestion of a broad trough over

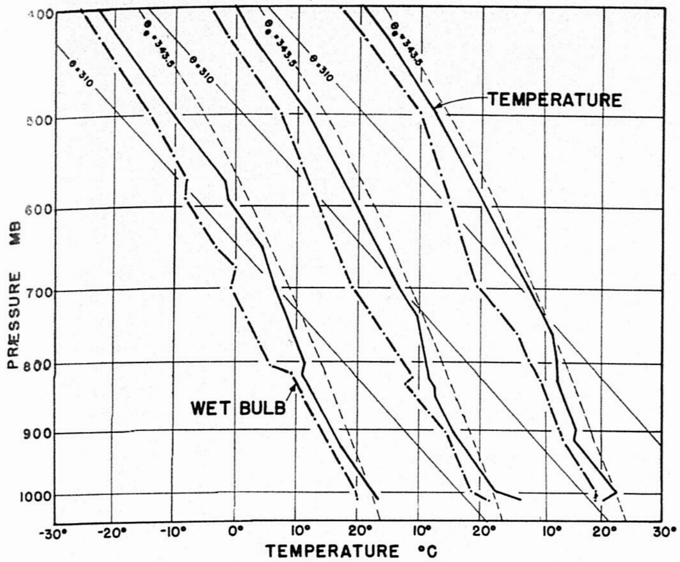

FIGURE 8.—Funnel cloud proximate sounding (center), Lihue, Kauai, 0300 GMT June 1, 1951 (1700 HST May 31), made about 1 hr. before and 16 mi. east-northeast of a waterspout. Soundings to left and right are the *antecedent* and *subsequent* soundings respectively, taken approximately 12 hr. before and after the *proximate* sounding.

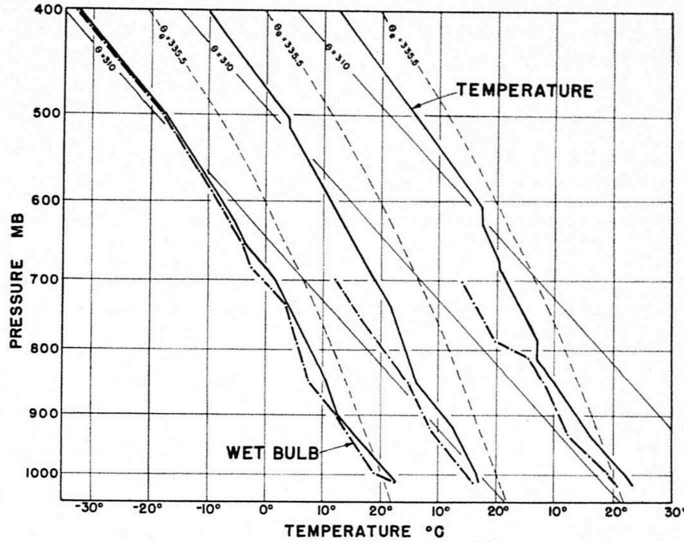

FIGURE 9.—Funnel cloud proximate sounding (center), Honolulu, Hawaii, 1500 GMT March 2, 1952 (0500 HST March 2), made less than 3 hr. before and about 25 mi. northwest of a waterspout. Soundings to left and right are the *antecedent* and *subsequent* soundings, respectively, taken approximately 12 hr. before and after the *proximate* soundings.

the central Pacific, but pressure gradients were very weak and the winds correspondingly light.

Although humidity was measurable to above the 400-mb. level (see fig. 8), it approached saturation only at lower levels. The antecedent sounding is, on the whole, moister than those which follow, and its inversion and abrupt decrease in moisture with height more typical of trade wind conditions. Convective instability is present below the inversion, and conditional instability both there and again above the level of about 600 mb.

The proximate sounding suggests that subsidence may have been occurring. The slight inversion previously near 810 mb. is now a shallow isothermal layer at 840 mb.; and the base of the conditionally unstable layer has descended to 740 mb. Twelve hours later, in the subsequent sounding, the continued lowering of the stable layers has brought the base of the inversion to 915 mb. and of the conditionally unstable layer to 760 mb. Below the 900-mb. level all three soundings in places approach or exceed absolute instability. Between about 900 and 500 mb., a slight warming of 1° or 2° C. is evident.

The LCL shows little change from the antecedent to the subsequent sounding, while free convection, if attained at all, is capped by the upper stable layers. The Showalter Index suggests *higher* parcel stability in the proximate sounding than in those which precede or follow it.

(3) *March 2, 1952, 0850 HST, 12 miles southeast of Koko Head, Oahu.*—Waterspouts were observed on two successive days during this period. The first occurred at 0850 HST on March 2, some 25 mi. from the radiosonde release point (WBAS, Honolulu) and less than 3 hr. after the beginning of a delayed 0600 HST (1600 GMT) flight.

The preceding day a surface trough had brought heavy rains and thunderstorms to the Hawaiian Islands and blanketed the upper slopes of the higher mountains with snow. On March 2 isolated thunderstorms were still being reported. Surface pressure gradients were very weak. Winds were light and variable, and by mid-day had given way to sea breezes. Aloft, a trough lingered over the Islands.

The antecedent raob (fig. 9) made at Honolulu at 1700 HST the evening before, when a thunderstorm was occurring near Oahu, is saturated above the 650-mb. level and in several places below. The sounding is dry adiabatic from the surface to 900 mb., conditionally unstable above, and convectively unstable throughout, except from about 730 to 850 mb.

The proximate sounding, made 11 hr. later and in improving weather, is greatly altered. The extensive cooling, which had accompanied the trough, continues on a more modest scale from the surface to 600 mb., with a maximum decrease of about 4° C. at 800 mb., and a very slight warming above. Even more conspicuous is that the entire air column is much drier than it had been, with motorboating above the 700-mb. level. The rapid decline in moisture with height, and the decreased lapse above the 850-mb. level strongly suggest stabilization leading to the re-establishment of a subsidence inversion. The dry adiabatic layer is farther aloft—from 920 to 850 mb.—and with diurnal heating can be expected to extend down to the surface (as it does, in fact, in the subsequent sounding).

By the time of the subsequent sounding, subsidence had lowered the top of a small isothermal layer from 500 mb. (on the proximate sounding) to 600 mb., and further diminished the moisture above the 800-mb. level. Recovery from the low temperatures of the trough passage has made the subsequent sounding everywhere from 2° to 5° C. higher than the proximate, and more stable from 810 to 600 mb. The isothermal layer at 810 mb., coupled with the sharp moisture cutoff, now very much suggests a trade sounding.

Interestingly enough, however, both Lihue to the north and Hilo to the south retain deep moist layers: to 12,000 ft. and 14,000 ft., respectively.

As table 6 shows, the levels of condensation and free convection are somewhat higher on the proximate than on the antecedent and subsequent soundings, even when corrected for diurnal heating; and in agreement with this indication of increased parcel stability nearer the time the funnel occurred, the Showalter Index is also appreciably greater then than either 12 hr. earlier or later.

(4) *March 3, 1952, 1850 HST, off Diamond Head, Oahu.*—On the day following that just described, a small waterspout was reported off Diamond Head, Oahu, less than 2 hr. after the 1700 HST (0300 GMT) radiosonde release at WBAS, Honolulu, 8 mi. to the west.

The day had been sunny, with a few convective clouds and showers (some of them exceptionally heavy) scattered over the island interiors by afternoon. Thunderstorms were no longer present in the vicinity, but distant lightning had been reported to the northeast. Surface winds were generally easterly around a large High far to the north. At 500 mb. an intense Low was centered over Hawaii.

The antecedent sounding (fig. 10), which follows by 12 hr. the subsequent sounding for the March 2 waterspout, is virtually identical with it above the 600-mb. level, although markedly different below. Convective instability is present throughout and conditional instability from 1000 to 800 mb. and above the 600-mb. level. The isothermal lapse and moisture cutoff, which on the previous sounding had seemed to presage the reestablishment of a subsidence inversion, are no longer present. Moisture is measurable to 600 mb., but nowhere reaches saturation.

By the time of the proximate sounding, afternoon heating had steepened the lapse to dry adiabatic in a deep layer extending from the surface to 865 mb.—a destabilization augmented by cooling of 2° to 3° C. between 500 and 600 mb. Above the 860-mb. level moisture decreases sharply. Motorboating begins at 650 mb., and the sounding is convectively unstable throughout.[10]

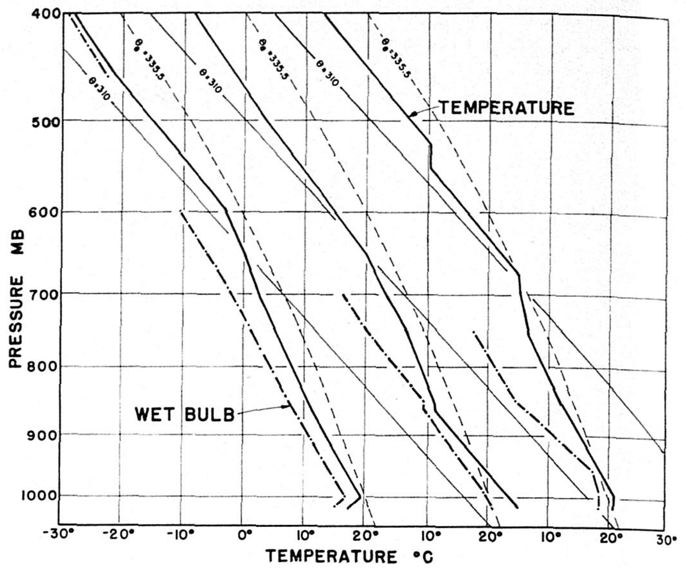

FIGURE 10.—Funnel cloud proximate sounding (center), Honolulu, Hawaii, 0300 GMT March 4, 1952 (1700 HST March 3), made less than 2 hr. before and 8 mi. east of a waterspout. Soundings to left and right are the *antecedent* and *subsequent* soundings, respectively, taken approximately 12 hr. before and after the *proximate* sounding.

Restabilization is apparent in the subsequent sounding, with warming everywhere but in the radiatively-cooled surface layer. The isothermal lapse between 520 and 550 mb., the nearly dry adiabatic layers above and below, and the stable layer from 670 to 760 mb.. all strongly suggest subsidence. Moisture drops rapidly above the 950-mb. level and motorboating occurs above the 750-mb. level.

The decrease in stability from the antecedent to the proximate sounding, and the later restabilization, are reflected particularly in the Showalter Index, which shows parcel stability much diminished prior to the waterspout and then increasing again.

(5) *March 18, 1955, 1710 HST, Hilo Bay.*—A waterspout formed over Hilo Bay within minutes of the 1700 HST (0300 GMT) radiosonde release at WBAS, Hilo, less than a mile away. A half hour later another developed in the same place. Both moved inland, but did little damage. Scattered showers, moderate at times, were occurring in the area. These were the first waterspouts observed in Hilo since 1943.

This was the nearest in time and space of the proximity soundings obtained in Hawaii. Also—and perhaps not entirely by chance—it most nearly presented the classical air mass modifications expected in the immediate vicinity of funnel clouds.

The islands lay within a narrow trough or col extending southward between large Highs from a Low 1,000 mi. to the north. Surface pressure gradients were flat. During the day gentle trades appeared from time to time in some

[10] The limited representativeness of these soundings is illustrated by the fact that despite the shallowness of this moist layer (the radiosonde evidently ascended through cloud-free air) intense showers (some of which yielded several inches of rain) were occurring from deep convective clouds within a very few miles of the observation.

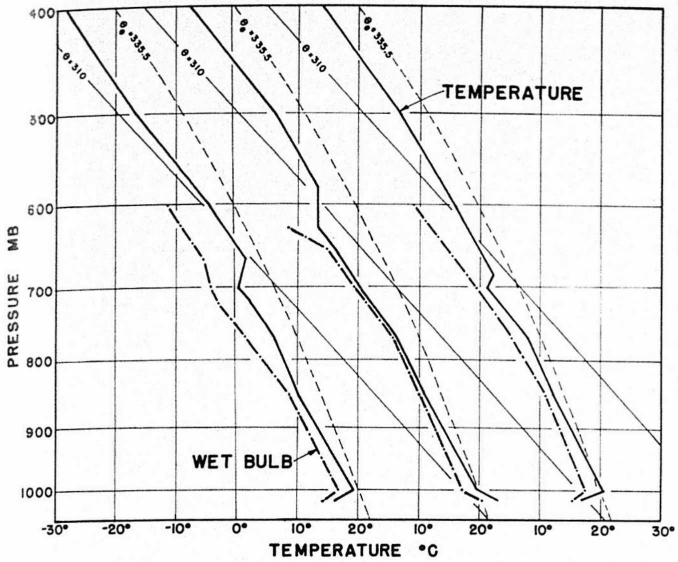

FIGURE 11.—Funnel cloud proximate sounding (center), Hilo, Hawaii, 0300 GMT March 19, 1955 (1700 HST March 18), made less than 1 mi. from and within minutes of a waterspout. Soundings to left and right are, respectively, the *antecedent* and *subsequent* soundings taken approximately 12 hr. before and after the *proximate* sounding.

localities, but winds in most places were light and variable. Aloft, a trough line lay just west of the islands.

The antecedent raob (fig. 11), made 12 hr. before the waterspouts appeared, is superficially much like a trade wind sounding in possessing an inversion, but the air beneath it is rather drier than is ordinarily the case, and does not show a moisture break at the inversion base. Except through the inversion, it is conditionally and convectively unstable throughout. Moisture falls off rapidly with height and motorboating occurs above the 600-mb. level.

The ensuing sequence of destabilization and restabilization is typical of that in a subsiding subtropical air mass disturbed by a transient easterly wave, upper trough, or other event conducive to vertical stretching, and resembles what has been described for certain tornado situations in the continental United States.

Since the major changes in stability involved primarily the lower atmosphere, they are best reflected in computations based on surface data (see table 6). Thus, the Lifted Index[11] was, respectively, +3.6, −7.5, and +5.7 (the large negative value indicates considerable parcel instability). Also the level of free convection, which was not reached at all in either the antecedent or subsequent soundings, fell in the proximate sounding to 950 mb., where it coincided with the lifting condensation level. On the other hand, the Showalter Index, which only implicitly represents conditions below the 850-mb. level, suggests greater parcel stability in the proximate sounding than in those earlier or later.

These soundings have been presented here more for the information of those interested in air mass properties near funnel clouds in the maritime subtropics than because they were felt to be in any other way distinctive. While the last series does illustrate the air mass modifications believed to exist in the vicinity of funnel clouds, such changes occur far more commonly in Hawaii and elsewhere than do the funnels themselves. On the whole, the soundings would seem to contain little of predictive or even of diagnostic value for entities of this scale, and in some instances inadequately reflect even the current weather.

9. SUMMARY AND CONCLUSIONS

The principal purpose of this report has been to describe the local and synoptic circumstances under which funnel clouds occurred in Hawaii during the period 1949 through 1960.

From what has been done it would appear that the 31 funnel cloud days of those 12 years were distributed among all the major climatic regimes characteristic of that area, although not at all in proportionate frequencies. Most commonly associated with them was what is referred to locally as "Kona Weather," typified by weak or diffuse pressure gradients, warm humid afternoons, light and variable winds, and convective clouds and showers. Trades, on the other hand, although climatologically dominant, were well established on only 4 funnel cloud days, and on 10 others were too weak to avoid replacement by afternoon sea breezes. The upper level charts (principally at 500 mb.) showed troughs or closed Lows directly over the area or slightly to the west on 20 of the 31 days, and flat or ill-defined pressure gradients on the others.

Air mass properties on days with funnels ranged from those typical of the trades to, in a single instance, the destabilization and moist layer deepening classically precursory to tornadoes in the continental United States. On that one occasion, the sounding—perhaps significantly—was obtained within a very few minutes of, and less than a mile from, a waterspout. The variety otherwise exhibited by soundings made on funnel cloud days, including several fairly near funnels in time and space, may indicate only that the air mass structure implied by funnel clouds is highly transitory and ordinarily to be found only in their immediate vicinity.

It need scarcely be pointed out that studies of this kind, which focus their attention on the circumstances under which particular events occur, to the virtual exclusion of the far more numerous occasions when they do not, cannot be expected to yield the necessary and sufficient conditions for their occurrence or criteria useful

[11] The Lifted Index is the actual (sounding) temperature at 500 mb. minus that of a parcel which ascends moist adiabatically from the lifting condensation level. See [4] for a discussion of the Lifted Index as used in severe storm forecasting in continental United States.

in diagnosis and prediction. Granting both the essential uniqueness of each meteorological state, and that some funnels must inevitably have gone undetected or unreported, it still would appear that funnel clouds were far less numerous during the 12 years covered by this report than were each of the situations in which they occurred.

While the destructiveness of tornadoes has directed much attention to the identification of their precursors, little comparable has been done with such ordinarily much less ominous events as waterspouts and funnels aloft. In addition, those factors which, in the continental United States, appear to be most indicative of tornado-prone situations require for their analysis a far denser network of surface and upper air observations than exists in the central Pacific. Hence direct comparisons between the significant concomitants of funnels in the Hawaiian area and those elsewhere are difficult to make. Nevertheless it does appear that the close association of tornadoes in the continental United States with active cold fronts, squall lines, and thunderstorms and with upper wind maxima or strong influxes of moisture is not matched by Hawaii's funnel clouds, whose diversity of circumstance would appear rather to support Flora's [3] judgment that for waterspouts, at least, there are "no hard and fast rules."

Do waterspouts in Hawaii build downward from clouds or upward from the sea? The former are regarded as "true" waterspouts—that is, as tornadoes occurring over water, while the latter (which appear to form over a still layer of superheated and unstable air resting on the water, and often under cloudless skies) are genetically more comparable to dust devils. The miniature spout described later may have been of this type.

The question, a perennial one, might be more readily answerable had the original observations been made with it in mind; but the incompleteness of the actual reports precludes more than a brief survey of the possibilities. Conceivably, for example, air warmed over land during Kona Weather, but retained there by onshore breezes during the day, could with the weakening of the sea breezes toward evening move outward over the sea; but there is no evidence that this occurs. The fact that most waterspouts in Hawaii occur during the cooler half-year, when the adjacent seas are warmest relative to the overlying air (by 2° or 3° F.) would also place the impetus for convection at the sea surface (although by a mechanism very different from that just described).

On the other hand, although only a few reports have explicitly associated waterspouts with parent clouds, the high incidence of funnels aloft (11 of the 31 funnel clouds were of this type), each presumably an incipient waterspout or tornado, would seem to argue that most waterspouts in Hawaii do originate in this way.

A more basic, yet related, consideration suggested by this study concerns the degree to which the Islands influence phenomena occurring essentially over the open sea or serve primarily as a vantage point from which merely to observe them. A subsidiary question is that of the relative proportion of funnels of local origin, as opposed to those associated with synoptic entities large enough to be detected by the sparse observational network in the Hawaiian area. The intermediate possibility—that some of the funnels may have accompanied synoptic perturbations of meso- or even micro-scale—is not at all unlikely, but at present is quite beyond determination.

Obviously, the Islands (as is true of any land mass) do influence the superambient air thermally and through topography. These are by no means independent, however. Terrain elevates the heat source, and hence the effects of heating, into the atmosphere above the ground layer, thus extending convection to greater heights and augmenting with an anabatic wind the development and intensity of the sea breeze; and, conversely, convective currents above even a flat island present a quasi-orography to the synoptic wind.

That the wind field also undergoes marked topographic distortion by the Islands is, of course, well known both through direct observation and even more dramatically through the striking orographically dependent variations in the magnitude and distribution of rainfall. The effect of topography of itself in generating funnels could ensue indirectly from the release of convective instability by orographic lifting, as well as more directly by imparting vorticity to the air flow, particularly on days of strong wind. Lee whirls and eddies both with horizontal and vertical axes are quite commonly observed in many localities and on all scales from the roll clouds of mountain ranges to the swirls produced by the edges of buildings and other relatively small obstacles.

Four of the funnels in this report occurred with strong and gusty trades (small craft warnings were out on two of the days). All were in the island lees and *could have been* topographically induced; but there is no way to ascertain this. In fact, on two of these four days a trailing cold front may have been in the area, and on another a shear line. Yet that the situation is probably more complex than this is suggested by the fact that while all these conditions are not at all uncommon, funnel clouds apparently are. Of the remaining 27 funnel cloud days, only 2 had higher than usual winds, but these were in Kona Storms which brought widespread thunderstorms and flooding rains to the Islands—and presumably the observed funnels, as well.

The role of intense surface heating in producing convection and eddies needs even less discussion. Dust devils and the tornadoes observed over forest fires and other conflagrations are familiar examples of whirls forming over local "hot spots"; and Dessens [2] appears recently to have produced rotatory funnels artificially out-of-doors over a square bank of oil burners.

As was stated earlier, most of Hawaii's funnel clouds occurred on days of abundant sunshine, when the absence of the trades, or of other regimes which continually circulate fresh marine air over the Islands, permitted afternoon temperatures and humidities to rise and convective cloudiness and showers to develop. Here the Islands may indeed have constituted such a hot spot amidst the relatively cool sea. (This is suggested also by the afternoon maximum in funnel cloud frequency.) Augmenting convection on such days was the convergence of the sea breezes, which were everywhere evident along the island peripheries; and this may well have constituted a much more important impetus to convection than did simple heating, alone. Further complicating the patterns of heating, convection, and convergence is the complex topography. The resulting convective phenomena also tended to be more intense when an upper trough or Low lay above the Islands, and on a number of occasions the possible presence of surface convergence on a synoptic scale—a shear line or asymptote or a front presumed extinct—could neither be precluded nor confirmed.

In all, therefore, it did not seem possible to sort out "purely" topographic from "purely" heating effects, or to separate either from factors of synoptic scale, such as upper troughs or Lows, or even more subtly, suspected shear lines or residual cold fronts.

Nevertheless, a tentative attempt has been made to assess local and large-scale contributions on each of the 31 funnel days. In view of our admittedly limited understanding of the factors involved in the formation of funnel clouds, this is a hazardous undertaking whose physical meaningfulness cannot be strongly defended; but it represents the best judgment of the authors, based on all the information available to them concerning the circumstances under which these funnel clouds occurred. The results, on an arbitrary scale, are given in table 7.

The range extends from funnels which were "primarily local" in origin, that is those in which the effects of topography, heating, sea breeze convergence, etc., appear by far to have predominated, to those whose genesis was "primarily synoptic," in being related to synoptic events on a large scale, and in which the islands appeared to have exercised no critical role. Most of the days of widespread thunderstorm activity fall in the latter category. Between these extremes—each of which, interestingly enough, contains a larger number of instances than any other category—lie those in which both local and synoptic influences are believed to have conjoined, to a greater or lesser degree. The distribution is distinctly bimodal.

TABLE 7.—*Local and synoptic contributions in Hawaiian funnel clouds, 1949–1960*

Arbitrary scale	Contribution	Number of funnels	Percent
0	Local only*	0	0
1	Primarily local	6	19
2	Local predominates, but significant synoptic	5	16
3		5	16
4	Local and synoptic about equal	2	6
5		1	3
6	Synoptic predominates, but significant local	1	3
7		2	6
8	Primarily synoptic	2	6
9		7	23
10	Synoptic only	0	0

*Local: combined influence of topography and heating.

These categories are distinguishable only by the authors' degree of certainty of the suspected synoptic or local influence. Thus, to call a funnel cloud of "primarily synoptic" origin can imply, then, not that the effects of topography or of heating were entirely absent (how could they have been?) or even negligible, but only that the synoptic situation which existed is ordinarily, and was in this specific instance, associated with intense convective phenomena over a large area; and that, therefore the occurrence of a funnel cloud near Hawaii could not be regarded as anomalous, even without any local contribution.[12]

Some confirmation of the physical meaningfulness of the classification is suggested by the marked seasonal differences between the degrees of local and synoptic control. During the warmer half-year, local influences predominated on 13 of the 14 funnel cloud days. The average rank, on the arbitrary scale of table 7, was 2.5. In the cooler half-year, synoptic influences predominated on 12 of the 17 funnel cloud days, with an average rank of 6.7.

APPENDIX

SOME NOTEWORTHY HAWAIIAN FUNNEL CLOUDS

It may seem somewhat surprising, in view of the number observed offshore, that more waterspouts have not wreaked damage upon the coasts or moved inland to become tornadoes. Some of the spouts sighted out to sea could undoubtedly have proved dangerous had they done this, but as yet there has been neither widespread destruction nor any known fatality from a Hawaiian funnel cloud.

But not all funnels have remained harmlessly aloft or out to sea, or behaved docilely over land. A number have been mildly destructive. Perhaps the most violent of those known to the authors was a waterspout which occurred in March 1933, during the gusty southerly winds and heavy rains of a Kona Storm. When first noticed, it was several miles off Honolulu Harbor, but it quickly moved inshore from the south, accompanied by "a streak of lightning and a bolt of thunder."

A newspaper report of the day [5] described it as "huge", and went on:

> The spout curled black and threatening high into the air and then burst in a cascade of spray. A moment later the wind, almost of hurricane force, swept down upon the quarantine wharf . . . and curled up a section of the iron roof as though it were tissue paper. Across the harbor it struck with full force (against Pier 16) and ripped away almost the entire side of the roof. Several of the sheets of corrugated iron were hurled across the street and crashed through a section of the building opposite . . . Automobiles

[12] For specific examples of the application of this classification, note that the five proximity funnels described earlier were rated, respectively, by date, as: 1, 2, 9, 6, and 8 on the arbitrary scale of table 7.

> parked in the street were damaged by the falling sheets of corrugated iron, while wires along King Street were severed . . . Trees in Aala Park also felt the blast. Within a space of 10 seconds the entire area was showing signs of devastation.

Three persons were injured and harbor activities disrupted.

Other memorable Hawaiian funnel clouds include the family of spouts observed revolving about one another 10 mi. off the west coast of Kauai at daybreak of February 9, 1880; the large clockwise-rotating waterspout, accompanied by "flashes of vivid lightning," about a mile off Honolulu Harbor on May 21, 1877; and the miniature spout, "about ten feet high," that moved onshore on February 8, 1934, and shattered against a stone wall a short distance inland.

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